

Calculation of Green Innovation Efficiency and Analysis of Improvement Path Mechanism for Chinese Manufacturing Listed Companies

Han Gao^{1*}

¹ School of Business Administration, Anhui University of Finance and Economics, Bengbu, China

Email Address

3202200355@aufe.edu.cn (Han Gao)

*Correspondence: 3202200355@aufe.edu.cn

Received: 25 June 2024; Accepted: 14 July 2024; Published: 27 July 2024

Abstract:

Against the backdrop of the “dual carbon” goal, green development cannot do without the powerful driving force of green innovation, which promotes high-quality development. As the core initiator and implementer of innovation, we bear the significant responsibility of promoting sustainable development, that is, accelerating innovation to promote the coordinated development of economy and environment. Based on the super efficiency SBM model, the green innovation efficiency of manufacturing enterprises in Chinese listed companies from 2015 to 2021 was calculated. The results showed that the green innovation efficiency of the manufacturing industry showed an upward trend, and the cities with higher efficiency were mainly concentrated in the southern and central parts of the country.

Keywords:

Green Innovation Efficiency, SBM, Manufacturing

1. Introduction

With the rapid development of domestic and international economies, the irregular climate changes caused by global warming and the serious impact of human activities on the environment have seriously hindered the development of the entire economy and society, which has also brought significant challenges to countries around the world. As a global manufacturing powerhouse and the world's largest energy consumer, China is facing severe environmental pollution and energy consumption issues while striving to develop its own economy and technology. In response to global climate change and the increasingly severe environmental pollution problem, China has proposed the major strategic goal of “carbon peak and carbon neutrality”. The government is implementing increasingly strict environmental regulations, and society is constantly increasing its demand for green products. Manufacturing enterprises are facing significant challenges in transitioning to green and low-carbon production models as soon as possible. In the 14th Five Year Plan, it is proposed that

China should adhere to the real economy as the focus of economic development. Currently, China should accelerate the construction of a strong manufacturing country, deeply develop advanced manufacturing industries, and promote the high-end, intelligent, and green development of the manufacturing industry. China's economic development model has always relied on the characteristics of high investment and high pollution emissions. The rapid development of the economy is accompanied by environmental degradation caused by pollution and energy shortages caused by overexploitation. Therefore, vigorously developing enterprises to carry out green and low-carbon transformation and achieve coordinated economic and green development is a strategy formulated by China to promote high-quality development, and it is also a continuous change that countries need to carry out in the global environment of environmental pollution and energy shortage. The most powerful driving force for enterprise green transformation is green technology innovation. Enterprises can achieve both product revenue and green transformation through green technology innovation, ultimately achieving long-term sustainable development. Green technology innovation aims to reduce environmental pollution and energy consumption as much as possible through energy conservation and emission reduction throughout the entire production process, from product design, production, packaging, and sales to final recycling, which is more targeted at the transformation of production modes in the manufacturing industry. In recent years, with the rapid development of the digital economy, various industries have begun to use digital transformation for green innovation. Manufacturing enterprises have also begun to use digital technologies such as big data, robots, cloud platforms, and artificial intelligence to reform production and sales models.

The concept of green innovation was first proposed in 1996, stating that it is a new product or process that can reduce environmental pollution. At present, domestic and foreign scholars' research on green innovation is mainly divided into three parts: efficiency measurement, spatiotemporal differentiation and network evolution, and influencing factors. At present, scholars mostly use traditional stochastic frontier analysis (SFA), data envelopment analysis (DEA), and super efficiency SBM models that consider unexpected outputs to measure the efficiency of green innovation. CUI et al.[2] used SFA and kernel density functions to study the trends of green total factor productivity in 36 industrial sectors in China from 2000 to 2016, and explored their key driving factors using the system generalized moment of moments method; Zhang Feng et al. [3] also used SFA to construct a three-stage efficiency measurement model to measure the green technology innovation efficiency of high-tech industries, and found that there is significant regional heterogeneity in the green technology innovation efficiency of high-tech industries, with the eastern region being higher than other regions. In recent years, the use of Data Envelopment Analysis (DEA) has become increasingly widespread. For example, DENG et al. [4] used the super efficient DEA model to evaluate regional innovation performance based on provincial panel data in China from 2001 to 2016; Qian Li et al. [5] divided green innovation activities into two stages based on the two-stage innovation value chain theory: technological research and development and achievement transformation. After calculating the efficiency, they analyzed the influencing factors of innovation efficiency in each stage; Based on the data of prefecture level cities from 2005 to 2018, Sun Zhenqing et al. [6] studied four urban agglomerations and used a three-stage DEA method to measure the collaborative innovation efficiency of the four major urban agglomerations in order to avoid the influence of external factors. In response to the traditional DEA model's failure to consider "slack variables" and

inability to reasonably address efficiency evaluation issues under conditions of unexpected output, scholars have adopted the SBM model to measure green innovation efficiency. Cao Ling et al. [7] used a non radial, variable return to scale Super SBM model to measure the efficiency of China's industrial green innovation from 2005 to 2019; Wu Chuanqing et al. [8] used the Super SBM model to measure the green innovation efficiency of the national equipment manufacturing industry, considering both expected and unexpected outputs in the output possibility. Overall, different methods can be used to measure efficiency depending on the research content.

2. Model Construction and Data Sources

2.1. Research Method: Super Efficiency SBM Model Considering Unexpected Output

In domestic research, data envelopment analysis and stochastic frontier analysis are commonly used to measure the economic efficiency of a single output. The green innovation efficiency of enterprises, given the complexity of the enterprise as a research subject, makes it difficult to accurately measure its efficiency using a single output indicator. Therefore, by adopting multiple indicators and dividing output indicators into expected and unexpected outputs, a more rigorous measurement of green innovation efficiency can be carried out. The traditional DEA radial model cannot take into account the slack variables of invalid units. Therefore, scholars have innovated the SBM model to modify the basic DEA model. On the basis of solving the problem of weak effective data, it achieves the common measurement goal of non single indicators, making the measurement results closer to the green innovation of enterprises.

This article is based on the perspective of output, treating each province as a single Decision Making Unit (DMU). Due to the unexpected output of industrial waste and other waste generated by regions in the innovation process, this study adopts the super efficiency SBM model, where each decision unit includes three parts: input, expected output, and unexpected output. According to Tone's method [9], the model is defined as follows:

$$\min \rho = \frac{1 + \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{ik}}}{1 - \frac{1}{q_1 + q_2} (\sum_{r=1}^{q_1} \frac{s_r^+}{y_{rk}} + \sum_{t=1}^{q_2} \frac{s_t^{b-}}{b_{tk}}} \quad (1)$$

It satisfies the following constraint conditions:

$$\sum_{j=1, j \neq k}^n x_{ij} \lambda_j - s_i^- \leq x_{ik} \quad (2)$$

$$\sum_{j=1, j \neq k}^n y_{rj} \lambda_j + s_r^+ \geq y_{rk} \quad (3)$$

$$\sum_{j=1, j \neq k}^n b_{tj} \lambda_j - s_t^{b-} \leq b_{tk} \quad (4)$$

$$1 - \frac{1}{q_1 + q_2} (\sum_{r=1}^{q_1} \frac{s_r^+}{y_{rk}} + \sum_{t=1}^{q_2} \frac{s_t^{b-}}{b_{tk}}) > 0 \quad (5)$$

$$\lambda, s^-, s^+ \geq 0; i = 1, 2, \dots, m; r = 1, 2, \dots, q; j = 1, 2, \dots, n (j \neq k) \quad (6)$$

In the above formula, ρ represents the efficiency value of green innovation, x_{ik} , y_{rk} , b_{tk} represents input, expected output, and unexpected output, s_i^- , s_r^+ , s_t^{b-} represents slack variables of input, expected output, and unexpected output, λ represents the

weight vector of the decision-making unit, m represents the number of input indicators, q_1 and q_2 represents the number of expected output indicators and unexpected output indicators, respectively.

In order to consider more scientifically, reliably, and globally, drawing on the research results of Guang Fengtao et al. [10], a green innovation efficiency measurement index system for the manufacturing industry is constructed as shown in Table 1. Among them, the input indicators include three aspects of factor inputs: capital, manpower, and energy, which are important supports for manufacturing enterprises to carry out green innovation activities; The output indicators are divided into two parts, namely the expected output of the enterprise's production activities and the unexpected output caused by pollution during the production process, which are the specific manifestations of the achievements of green innovation activities in the manufacturing industry. The expected output includes two indicators, namely the operating revenue of manufacturing enterprises and the number of green patent authorizations of manufacturing enterprises. The former reflects the economic value of green innovation activities, while the latter represents the technological value of green innovation activities. In addition, the discharge of wastewater, exhaust gas, and solid waste in the manufacturing process is comprehensively considered in terms of unexpected output [11]. The larger the discharge of industrial waste, the more severe the environmental pollution caused by the production process of the enterprise, and the greater the unexpected output.

Table 1. Evaluation index system for green innovation efficiency in manufacturing industry.

Indicator type	Indicator composition	variable
Investment indicators	Capital investment	R&D investment
	Human resource investment	Full time equivalent of R&D personnel
	Energy investment	Total energy consumption
Output indicators	Expected output	business income
		Number of green patent authorizations
	Unexpected output	Emissions of three wastes

2.2. Data sources and processing

Based on the data of Chinese A-share listed manufacturing enterprises from 2015 to 2021, the data was screened according to the following criteria: firstly, samples of ST and * ST listed companies and samples with missing financial indicators were excluded. Secondly, in order to reduce the influence of extreme values, all continuous variables were truncated at the 1% and 99% levels. The specific enterprise level data for measuring the green innovation efficiency of manufacturing enterprises in the article comes from the CSMAR database, and is aggregated by city after excluding listed and delisted enterprises during the research period. The remaining city level data comes from the "China Urban Statistical Yearbook" (2015-2021), and due to some missing data, linear interpolation is used to supplement it. In order to exclude the impact of the COVID-19 epidemic on the production activities of manufacturing enterprises, the empirical results of this paper show some years before the epidemic.

3. Measurement of Green Innovation Efficiency in Manufacturing Enterprises

Using the super efficiency SBM model based on unexpected output, the green innovation efficiency of manufacturing listed companies in 31 provinces across the country from 2015 to 2021 was calculated. The results are shown in Table 2.

From the annual averages, Table 2 shows that the peak of green innovation efficiency of listed manufacturing companies occurred in 2019 and 2020. However, in 2021, due to the external impact of the COVID-19, manufacturing enterprises across the country will be at a standstill and unable to carry out production activities, resulting in a significant decline in the green innovation efficiency of manufacturing enterprises in most provinces, which is the lowest value in the measurement period. The most obvious impact is on Guizhou Province, as it is a tourist city. During the epidemic, due to restrictions on tourist travel, production enterprises in the entire Guizhou region were severely affected. In addition, overall, the green innovation efficiency of manufacturing enterprises has shown a steady upward trend year by year, reflecting the improvement of green innovation capabilities of manufacturing enterprises since the State Council issued the “Made in China 2025” as the first ten-year action plan for China to implement a manufacturing power on May 8, 2015.

From a provincial perspective, the green innovation efficiency of manufacturing enterprises in Shanghai has been leading during the measurement period and there is a significant gap compared to other cities with higher efficiency. This is because Shanghai, as an international trade and technology innovation center, has higher economic strength and innovation capabilities. Therefore, it plays a leading role in the development of green innovation in the national manufacturing industry. In addition, the green innovation efficiency values of Guangdong, Jiangsu, and Zhejiang cities have maintained a stable and high level. Among them, Jiangsu Province leverages its abundant scientific and educational resources, while Suzhou vigorously develops advanced manufacturing and ranks third in the “Top 100 Advanced Manufacturing Cities (2021) Research Report”, driving the rapid development of traditional manufacturing cities Changzhou and Wuxi. As the capital city of Zhejiang Province, Hangzhou leverages its leading digital economy and developed private economy to rank fourth in the “Top 100 Advanced Manufacturing Cities (2021) Research Report”, closely following Suzhou. Hefei, as an emerging comprehensive processing and manufacturing city, was selected as one of the first batch of national key cities for industrial operation. Later, it vigorously developed advanced manufacturing industries in the high-tech zone, radiating and driving the Huai River region, and promoting the accelerated development of northern Anhui. However, in provinces such as Yunnan, Shanxi, and Hebei, the low efficiency of green innovation in manufacturing enterprises may be due to their backwardness in environmental governance, resulting in excessive pollution and lagging behind in urban green development compared to other provinces.

From the perspective of spatial distribution, the efficiency results show a spatial differentiation pattern of high in the south and low in the north, and there is a significant spatial agglomeration effect. Shanghai and other provinces with more developed manufacturing industries, as well as southern provinces, have better green innovation efficiency of manufacturing enterprises compared to other provinces, and there is a certain spillover effect on surrounding provinces. Overall, it presents a decreasing pattern of “developed cities - southeastern coastal provinces - central provinces - northwestern remote provinces”. This is because economically developed provinces invest more in the green transformation of manufacturing enterprises compared to underdeveloped provinces, and can purchase more advanced equipment for harmless treatment of the pollution generated in the production activities of manufacturing enterprises. However, some manufacturing enterprises in underdeveloped areas cannot engage in production activities with lower energy

consumption and less pollutant emissions due to outdated equipment and other reasons. It can be seen that the number of provinces with low efficiency in green innovation for manufacturing enterprises across the country continues to decrease to none, while the number of provinces with medium efficiency fluctuates and the number of provinces with high efficiency increases. The continuous improvement of green innovation efficiency of manufacturing enterprises nationwide is mainly due to the government's policy tilt towards the manufacturing industry.

Table 2. 2015-2021 Empirical results of green innovation efficiency of manufacturing enterprises in various provinces across the country.

	2015	2016	2017	2018	2019	2020	2021	Average
Shanghai	1.233	1.237	1.350	1.39	1.296	1.332	1.330	1.310
Beijing	1.006	1.041	1.085	1.018	0.990	1.001	1.012	1.022
Tianjin	0.963	0.952	0.998	0.966	1.012	0.716	1.001	0.944
Hebei	0.318	0.5	0.623	0.681	0.692	0.665	0.483	0.566
Shanxi	0.459	0.435	0.425	0.520	0.509	0.651	0.415	0.488
Neimeng	0.128	0.213	0.223	0.312	0.305	0.301	0.180	0.237
Liaoning	0.503	0.589	0.622	0.601	0.623	0.706	0.665	0.616
Jilin	0.668	0.550	0.582	0.651	0.854	0.693	0.522	0.646
Heilongjiang	0.640	0.678	0.661	0.603	0.778	0.802	0.680	0.692
Shandong	0.538	0.602	0.665	0.518	0.544	0.583	0.471	0.560
Henan	0.502	0.583	0.301	0.624	0.573	0.696	0.489	0.538
Hubei	0.512	0.640	0.659	0.612	0.501	0.799	0.473	0.599
Hunan	0.413	0.501	0.592	0.301	0.591	0.599	0.441	0.491
Jiangsu	0.936	0.902	0.912	0.903	1.012	1.001	0.804	0.924
Zhejiang	1.021	1.026	1.002	1.001	1.011	1.102	1.041	1.029
Anhui	0.918	0.902	0.912	0.901	1.012	1.111	0.877	0.946
Fujian	0.964	0.957	1.045	1.065	0.938	1.07	0.625	0.952
Jiangxi	0.501	0.502	0.560	0.581	0.601	0.625	0.435	0.543
Guangdong	0.977	0.996	1.005	1.009	1.031	1.012	0.662	0.956
Guangxi	0.425	0.412	0.413	0.401	0.532	0.611	0.418	0.459
Hainan	0.936	0.903	0.984	0.993	0.901	0.921	0.701	0.905
Sichuan	0.621	0.611	0.602	0.612	0.606	0.792	0.603	0.634
Guizhou	0.302	0.308	0.311	0.323	0.407	0.411	0.402	0.352
Yunnan	0.663	0.601	0.645	0.632	0.691	0.706	0.566	0.643
Shaanxi	0.439	0.433	0.427	0.421	0.435	0.427	0.331	0.416
Gansu	0.312	0.323	0.331	0.325	0.338	0.341	0.334	0.329
Qinghai	1.001	1.005	1.002	0.989	1.012	0.999	0.998	1.001
Ningxia	0.657	0.378	0.465	0.569	0.815	0.871	0.860	0.659
Xinjiang	1.001	0.802	1.003	1.012	1.003	0.992	0.675	0.927
Xizang	0.503	0.412	0.452	0.441	0.512	0.492	0.399	0.459
Average	0.669	0.666	0.695	0.699	0.737	0.767	0.630	0.695

4. Conclusion and Suggestions

4.1. Main conclusions

This article uses the super efficiency SBM model to measure the green innovation efficiency of Chinese A-share manufacturing listed companies from 2015 to 2021.

Based on this, it analyzes the high and low green innovation efficiency of manufacturing enterprises in various provinces and conducts analysis according to provinces, regions, and other aspects. Conclusion: Based on the calculation of green innovation efficiency of Chinese A-share manufacturing listed companies, it was found that the green innovation efficiency of manufacturing enterprises in various regions showed a fluctuating upward trend during the research period. However, in 2021, due to the impact of the epidemic, the production activities of manufacturing enterprises in the vast majority of regions stagnated, resulting in a decrease in efficiency values. There is also a significant gap between different cities, with manufacturing enterprises in provinces such as Shanghai, Zhejiang, and Jiangsu having significantly higher green innovation efficiency than other cities. High efficiency provinces are mainly concentrated in the eastern coastal, southern coastal, central, and developed cities of China, and the number of high-efficiency provinces continues to increase over time.

4.2. Policy Suggestions

Make full use of resource advantages and adapt to local conditions. It is necessary for the government and enterprises to cooperate in seeking a path suitable for the green development of local manufacturing enterprises. For example, some regions with advanced economic level and green innovation technology development can accelerate their own green transformation and have a radiating and driving effect on surrounding cities by increasing investment in green innovation and improving the treatment of scientific researchers; For cities with ecological resources and environmental advantages such as Guizhou and Yunnan, it is necessary to fully utilize local green resources and improve green innovation and development capabilities under the concept of green development.

Establish assistance mechanisms and strengthen information exchange between cities. Provinces with high green innovation capabilities in manufacturing enterprises, such as Shanghai, Zhejiang, Jiangsu, etc., play a leading role in cross regional exchanges and cooperation, actively assisting relatively backward provinces by utilizing the “flat” network structure characteristics. Strengthen the flow of economic and talent resources between regions, establish a platform for urban green development exchange, promote the dissemination of green development knowledge, break the “Matthew effect” between cities, and balance the reception and spillover relationships of manufacturing enterprises in various regions. For cities with poor green innovation capabilities of manufacturing enterprises, they should actively learn the management methods of cities with higher green innovation capabilities, and develop an optimized set of management measures based on local conditions.

Accelerate the construction of transportation infrastructure in the region and promote the green transformation of enterprises. In order to strengthen the flow of green innovation elements between regions, each region needs to accelerate the construction of transportation infrastructure such as railways and highways between provinces and cities, reduce the cost of talent, knowledge and other green innovation elements flowing between cities, and weaken the negative impact of geographical distance on the formation of green innovation efficiency networks for regional manufacturing enterprises; Actively promoting the green transformation of enterprises, traditional manufacturing belongs to the secondary industry with high pollution and energy consumption. Enterprises should abandon traditional high pollution production methods and adopt high-tech such as new energy to carry out

low-carbon transformation of their production and operation models; Local governments should optimize and reform local environmental regulations, and develop a series of policies to incentivize enterprises to engage in green innovation activities based on the characteristics of local manufacturing enterprises.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

Funding

This work was supported by Anhui University of Finance and Economics Graduate Research Innovation Fund Project Name: Research on the Green Innovation Network Structure, Efficiency Measurement, and Spillover Mechanism of Manufacturing Industry under the Background of “Dual Carbon” (Project Number: ACYC2022122).

References

- [1] Fussler, C.; James, P. Eco-innovation: A break through discipline for innovation and sustainability. London: Pitman Publishing London. 1996.
- [2] Cui, H.; Wang, H.; Zhao, Q. Which factors stimulate industrial green total factor productivity growth rate in china? an industrial aspect. *Greenhouse Gases: Science and Technology*, 2019, 9(3), 505-518.
- [3] Zhang, F.; Ren, S.J.; Yin, X.Q. Green technology innovation efficiency and its scale-quality threshold effect of high-tech industries. *Science & Technology Progress and Policy*, 2020, 37(07), 59-68.
- [4] Deng, J.; Zhang, N.; Ahmad, F.; et al. Local government competition, environmental regulation intensity and regional innovation performance: an empirical investigation of Chinese provinces. *International Journal of Environmental Research and Public Health*, 2019, 16(12), 2130.
- [5] Qian, L.; Wang, W.P.; Xiao, R.Q. Research on the differences of green innovation efficiency of industrial enterprises in China from the perspective of shared input correlation. *China Population, Resources and Environment*, 2018, 28(05), 27-39.
- [6] Sun, Z.Q.; Li, H.H.; Liu, B.L. Comprehensive measurement and influencing factors of collaborative innovation efficiency of the four major urban agglomerations in China's eastern coastal areas. *Science & Technology Progress and Policy*, 2021, 38(02), 47-55.
- [7] Cao, L.; Yang, H.C.; Li, L.S. Spatial-temporal differentiation characteristics and dynamic evolution of industrial green innovation efficiency. *Studies in Science of Science*, 2022, 40(10), 1895-1906.
- [8] Wu, C.Q.; Shen, Y.Q. Research on the influence effect of the agglomeration of China's equipment manufacturing industry on green innovation efficiency. *Science & Technology Progress and Policy*, 2019, 36(05), 54-63.
- [9] Tone, K. A slacks-based measure of efficiency in data envelopment analysis. *European Journal of Operational Research*, 2001, 130(3), 498-509.

- [10]Guang, F.T.; Deng, Y.T.; Yi, M. Measurement of green innovation efficiency and its spatial-temporal differentiation characteristics: Taking the manufacturing industry in the Yangtze River Economic Belt as an example. *Science and Technology Management Research*, 2022, 42(06), 59-68.
- [11]Zhang, J.P.; Chen, S.Y. Financial development, environmental regulation and economic green transformation. *Journal of Finance and Economics*, 2021, 47(11), 78-93.



© 2024 by the author(s); licensee International Technology and Science Publications (ITS), this work for open access publication is under the Creative Commons Attribution International License (CC BY 4.0). (<http://creativecommons.org/licenses/by/4.0/>)